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Investigation on Stress Relaxation Behavior of High-Strength Steel Sheets Based on Elasto-viscoplasticity

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Abstract. Stress relaxation is the phenomenon where stress of materials decreases under constant strain. In several previous studies, it was found that the stress relaxation makes uniform elongation larger, showing a possibility that this phenomenon can be utilized to increase the forming limit in combination with the flexible slide motion of a servo press. However, the stress relaxation phenomenon has not yet been sufficiently clarified. Authors previously investigated the stress relaxation behavior by applying several models where stress relaxation was described as an elasto-viscoplasticity behavior. However, a unified and quantitative description of strain rate sensitivity of flow stress and stress relaxation has not been sufficiently studied. In this study, we investigated the influence of strain, strain rate and relaxation time on stress relaxation phenomena of high strength steel sheets. Strain rate sensitivity of flow stress was modelled with m-power law. Stress relaxation behavior was also successfully approximated by a model derived from the m-power law with the parameters obtained by strain rate sensitivity tests, which suggests that both the strain rate sensitivity and the stress relaxation were based on a unified elasto-viscoplasticity. The mechanisms of stress relaxation was also discussed through numerical analyses.

1. Introduction

High strength steel sheets are increasingly used in automotive body parts with the aim of weight reduction, but their use urgently requires further improvement in sheet forming technology to overcome difficulties such as poor formability, dimensional inaccuracy, etc. On the other hand, servo press facilities are becoming increasingly used in industry and many attempts are being made to bring out their characteristic features for enhancing the formability of high strength steel sheets. Although some of these attempts have been successful in finding the advantages of servo presses for improving formability, the mechanisms of such improvements have yet to be clarified in conjunction with the mechanical properties of the materials used.

Stress relaxation is the phenomenon where stress of materials decreases under constant strain. In several previous studies, it was found that the stress relaxation makes uniform elongation larger [1],

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showing a possibility that this phenomenon can be utilized to increase the forming limit in combination with the flexible slide motion of a servo press. However, the stress relaxation phenomenon has not yet been sufficiently clarified, i.e., very few studies have been carried out with detailed material tests and investigations with various material models.

Authors previously investigated the stress relaxation behavior by applying Krempl model where stress relaxation was described as an elasto-viscoplasticity behavior [2]. However, a unified and quantitative description of strain rate sensitivity of flow stress and stress relaxation has not been sufficiently studied.

In this study, we investigated the influence of strain, strain rate and relaxation time on stress relaxation phenomena of high strength steel sheets. Strain rate sensitivity of flow stress was modelled with m-power law. Stress relaxation behavior was also successfully approximated by a model derived from the m-power law with the parameters obtained by strain rate sensitivity tests, which suggests that both the strain rate sensitivity and the stress relaxation were based on a unified elasto-viscoplasticity. The macroscopic mechanisms of stress relaxation was also discussed through numerical analyses by introducing the m-power law into a finite-element code.

2. Experimental conditions

A 590-MPa class hot-rolled steel sheet with the thickness of 3.2 mm was used in the experiments. The specimens for uniaxial tensile tests and crosshead holding tests with the dimensions shown in Figure 1 (ISO 6892-1:2016 Test piece type 3) were prepared by machining. Markers for non-contact digital video extensometer (DVE-101, Shimadzu Corp.) were attached with the gauge length of 50 mm. Strain was also measured by high-elongation foil strain gauges KFEM-5-120-C1L3M2R (KYOWA) attached on the center of the specimens.

Experimental conditions are shown in Table 1. Four levels of strain rate were applied in the tensile tests. In the crosshead holding tests, where stress relaxation characteristics were obtained, were carried out followed by the tensile tests with given strain rate $\dot{\varepsilon}$ up to the nominal strain of 0.05. Tensile testing machine (AG-I 250 kN, Shimadzu Corp.) was used in these tests.

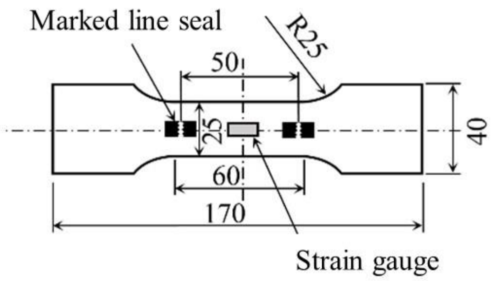

Figure 1. Dimensions of the specimen (Unit : mm)

Table 1. Experimental conditions

	Strain rate $\dot{\varepsilon}$ s^{-1}	Holding time t_H s
Tensile test	8.3×10^{-5}	-
	8.3×10^{-4}	-
	8.3×10^{-3}	-
	8.3×10^{-2}	-
Crosshead holding test	8.3×10^{-5}	30
	8.3×10^{-4}	30
	8.3×10^{-3}	30

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3. Results and discussions

3.1. Results of tensile tests and crosshead holding tests

Figure 2 shows the true stress – true strain curves obtained in the tensile tests. Strain rate sensitivity can be observed i.e. the flow stress becomes larger as the strain rate increases.

Figure 3 shows the stress relaxation behavior in true stress – true strain relation obtained in the crosshead holding test following the tensile test with the strain rate of 8.3×10^{-4} s^{-1}. Reduction in stress during the crosshead holding test can be observed, which corresponds to the stress relaxation phenomenon.

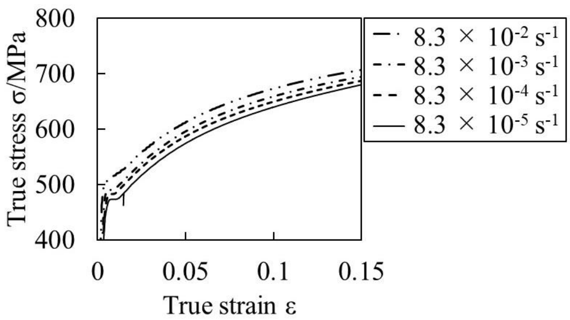

Figure 2. True stress-strain curves during tensile test

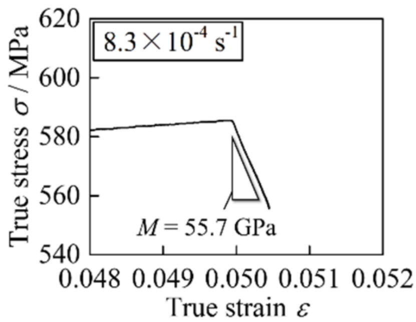

Figure 3. True stress-strain curve during crosshead holding test

3.2. Modeling of stress relaxation behavior

We assume that the flow stress during elasto-viscoplastic deformation can be described as the sum of internal (athermal) stress σ_i and effective (thermal) stress σ_t, as shown in Figure 4. In this study, we also apply the m-power law for the effective stress. Thus the following equation is assumed:

$$\sigma = \sigma_i(\varepsilon) + \sigma_t(\dot{\varepsilon}^{vp}) = \sigma_i(\varepsilon) + A(\dot{\varepsilon}^{vp})^m \tag{1}$$

where A and m are material constants. σ and ε^{vp} are flow stress and viscoplastic strain, respectively.

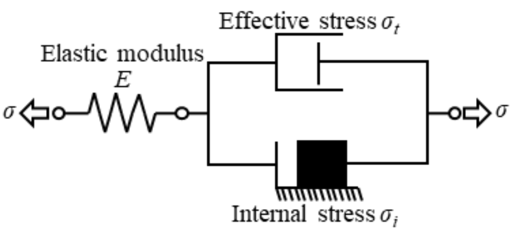

Figure 4. Elasto-viscoplasticity model

By using Eq. (1), stress relaxation model can be derived as the relation between time and stress as follows

$$\sigma = \left[\frac{1-m}{m} E' A^{-\frac{1}{m}} t_H + (\sigma_0 - \sigma_i)^{\frac{m-1}{m}}\right]^{\frac{m}{m-1}} + \sigma_i \tag{2}$$

Here, t_H and σ_0 are the holding time and the stress at t_H=0, respectively. E' is the apparent Young's modulus given by the following equation:

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$$E' = \frac{EM}{E+M} \tag{3}$$

where, E and M are Young's modulus of the material and the testing machine, respectively. M can be estimated to be 55.7 GPa from the slope of the stress relaxation region in stress-strain curve shown in Fig. 3.

A and m can be identified by using the tensile tests with various strain rates shown in Fig. 2. Since A and m are dependent on σ_i, we assume σ_i to be 500 MPa at ε = 0.049, which gives an accurate approximation by Eq. (3) of the stress relaxation behavior. Based on this assumption, A and m are determined through linear regression between $\log_{10}\dot{\varepsilon}$ *and* $\log_{10}(\sigma-\sigma_i)$, thus we obtained A = 125 MPa・s^m and m = 0.060.

Comparisons between stress relaxation behavior measured in the crosshead holding tests and approximation obtained by Eq. (3) based on m-power law with A and m obtained through above mentioned procedures are shown in Figure 5. Good correlations can be observed, i.e., discrepancies between the experimental results and the m-power law approximation are within the range of scattering in the flow stress among the test samples. These results suggest that both the strain rate sensitivity and the stress relaxation are based on a unified elasto-viscoplasticity and can be described by one numerical model.

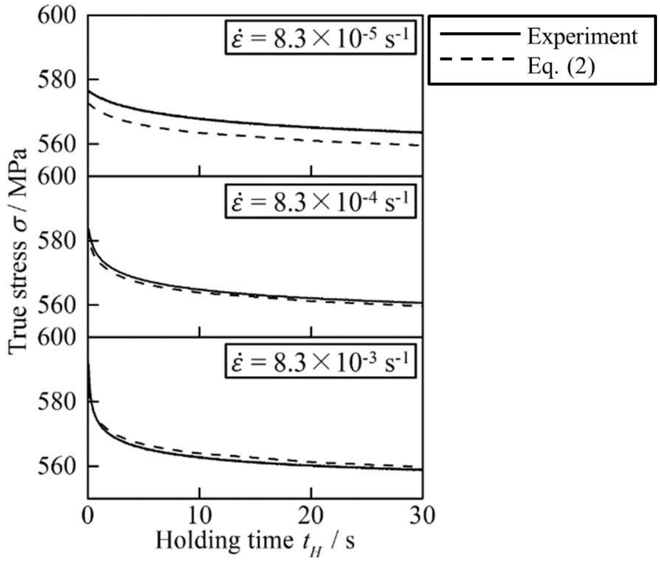

Figure 5. Relationship between holding time and true stress for various strain rate

3.3. Finite-element analysis of stress relaxation

Finite-element (FE) analyses were performed to simulate the stress relaxation processes and to analyse the behavior of stress and strain distribution in the test piece, which could never be measured in the material tests. The m-power law was introduced into the static-explicit FE code "STAMP3D" [3]. In this code, the updated Lagrangian rate formulation is employed to describe the finite deformation problem. Von Mises yield criterion and the associated flow rule are used. A static-explicit approach is applied in conjunction with the "r-min" method proposed by Yamada et al. [4] to define the size of the time step.

An elasto-viscoplastic model based on Fig. 4 was implemented in the code by assuming that the strain increment can be decomposed into elastic and viscoplastic components:

$$\Delta\varepsilon_{ij} = \Delta\varepsilon_{ij}^{e} + \Delta\varepsilon_{ij}^{vp} \tag{4}$$

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where, $\Delta\varepsilon_{ij}$, $\Delta\varepsilon_{ij}^{e}$ and $\Delta\varepsilon_{ij}^{vp}$ are increments of strain, elastic strain and viscoplastic strain tensor, respectively.

Stress increment can be written as:

$$\Delta\sigma_{ij} = C_{ijkl}^{e}\left[\Delta\varepsilon_{kl} - \Delta\varepsilon_{kl}^{vp}\right] \tag{5}$$

where, C_{ijkl}^{e} is the elastic constitutive tensor.

Assuming the flow rule for the effective stress described in Eq. (1), we obtain the constitutive equation for the viscoplastic part:

$$\dot{\varepsilon}_{ij}^{vp} = \frac{3\left(\bar{\sigma}_t/A\right)^{\frac{1}{m}}}{2\bar{\sigma}}\sigma'_{ij} \tag{6}$$

where, $\bar{\sigma}$, $\bar{\sigma}_t$ and σ'_{ij} are equivalent stress, equivalent thermal (effective) stress and deviatoric stress tensor, respectively.

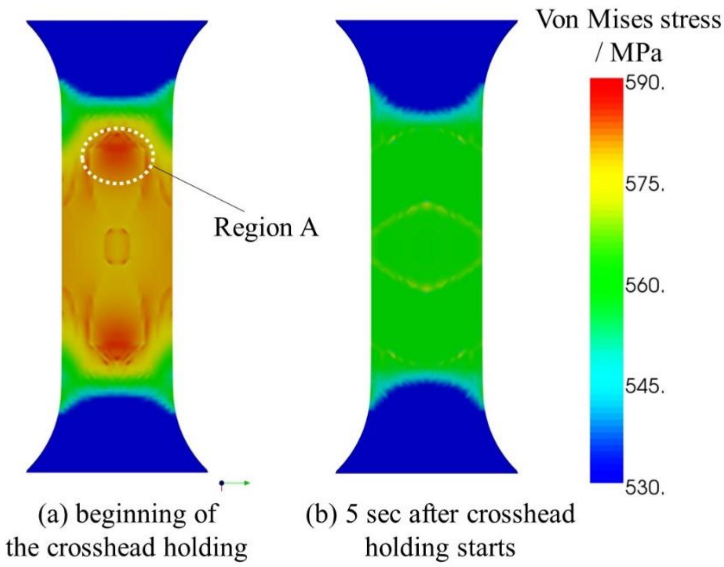

Figure 6. Distribution of von Mises stress obtained by FE simulations

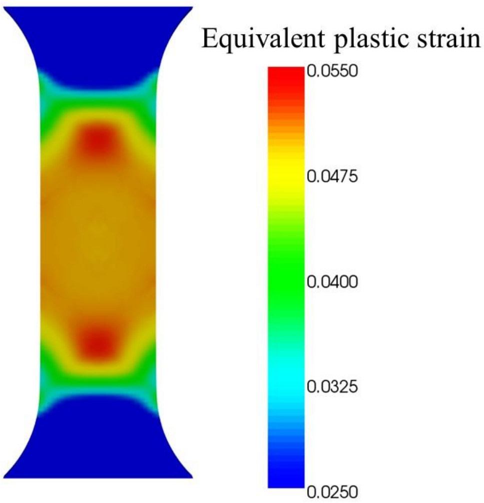

Figure 7. Distribution of equivalent plastic strain at the beginning of crosshead holding

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FE simulations of the uniaxial tensile and crosshead holding tests were performed. 8-node hexahedral elements were used to model the test piece shown in Fig. 1. Totally 18,000 elements with five layers of elements through the thickness direction were used. A = 125 MPa・s^m and m = 0.060 were used for the entire process. σ_i was set to be 500 MPa in the crosshead holding process. The uniformity of the stress distribution was not assured even in the tensile process with this geometry of specimen, which would rather have a possibility to give information on the deformation mechanisms of a forming process.

Figure 6 shows distribution of equivalent (von Mises) stress obtained by the FE simulations at the beginning of the crosshead holding and at 5 sec after the crosshead holding starts, assuming that the strain rate in tensile process is 8.3×10^{-1} s^{-1}. Level of the stress decreases during the crosshead holding process similarly to the experimental results shown in Fig. 3, showing the validity of above formulations.

Figure 6 also shows that the stress distribution becomes uniform after 5 sec of stress relaxation time, suggesting that the stress relaxation has an effect of improving the uniformity in the region subjected to plastic elongation. Figure 7 shows the distribution of equivalent plastic strain at the beginning of crosshead holding. Region A in Fig. 7 indicates the region where relatively larger equivalent plastic strain can be observed, which corresponds to the region with relatively larger equivalent stress in Fig. 6. This implies that the region with larger strain and larger stress shows larger stress reduction due to more significant stress relaxation, resulting in the elimination of non-uniformity in the stress distribution.

4. Conclusions

Uniaxial tensile tests and crosshead holding tests with a variety of strain rates were performed by using 590-MPa class hot-rolled steel sheets. Numerical model with m-power law for strain-rate sensitivity was applied to the stress relaxation behavior. FE analyses were performed by introducing m-power law into the static-explicit code. From these tests and analyses, the following conclusions were obtained.

Both the strain rate sensitivity and the stress relaxation were based on a unified elasto-viscoplasticity and can be described by one numerical model.

Numerical results by FE simulations suggest that the stress relaxation has an effect of improving the uniformity in the region subjected to plastic elongation. FE simulations with m-power law can be a useful tool to analyse the macroscopic stress relaxation phenomena by clarifying the stress and strain distributions which cannot be measured by material tests, showing a possibility to enable us to perform stamping simulations in industrial use to analyse the effect of forming speed in conjunction with stress relaxation phenomenon taken into account.

Acknowledgements

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